HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 11

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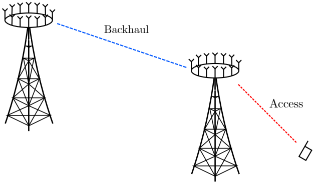
- Terahertz Communications
- Terahertz Generation
- Plasmonics
- Metasurfaces et al.

TERAHERTZ COMMUNICATIONS

- The electromagnetic (EM) spectrum between 0.1 THz to 10 THz is called the *THz band*.
- Naturally, higher carrier frequency yields higher bandwidth
  - Not necessarily higher channel capacity
- We can achieve bandwidths up to 20 Gbps
  - A typical 8K film requires 200 Mbps bandwidth!
  - For comparison, optical fibre communication can provide 39 Tbps bandwidth!
- THz communications provide a promising application for back hauling of base stations.



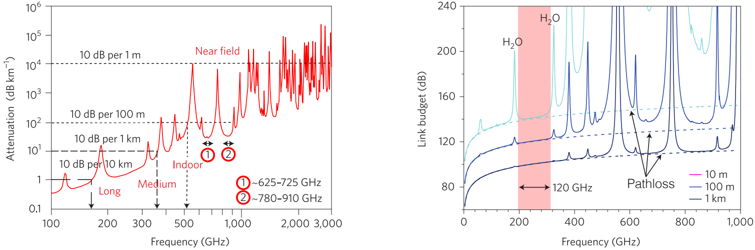
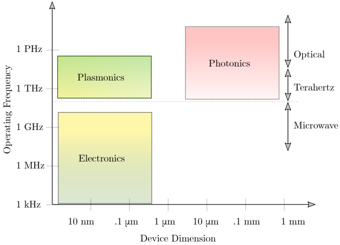
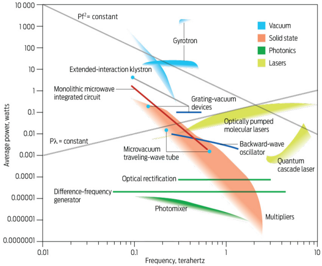


Figure 1: EM wave attenuation and free-space path-loss due to H_2O molecules in the air in the THz spectrum [Nagatsuma, T., *et al*. Nature Photon 10, 371-379 (2016)].

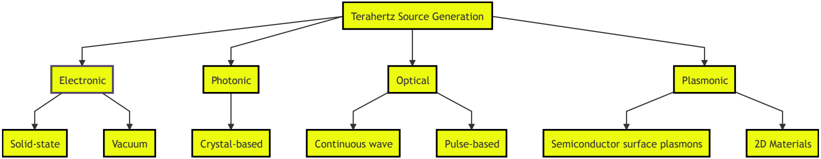
- Just like mmWave communications, THz waves have considerably high free-space pathloss
  - This requires even higher gain antennas ($\sim 100\,\text{dB}$)
- Current THz device technology does not allow us to increase the power levels
- Since THz lies in the middle of microwave and optical frequencies, we get the *best of both worlds*.
  - We have non-ionising waves
  - We can construct devices similar to optical technologies.





TERAHERTZ SOURCES

There are many ways to generate efficient THz signals. However, all the technologies have not fully developed to be widely available.



Today, we will focus on the plasmonic technologies.

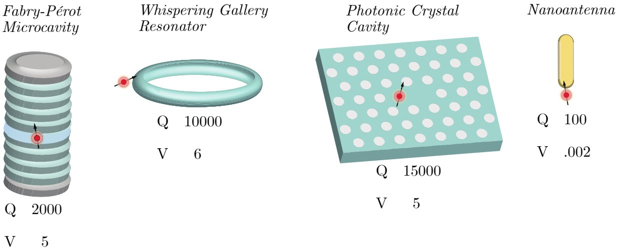


Figure 2: Different Source techniques at THz and optical frequencies.

- Microwave based vacuum tube technologies are extended to THz frequencies
  - The process involves conversion of modulated electron current to electromagnetic radiation
  - These are often called *fast-wave* devices
  - The phase velocity of the generated electromagnetic wave is greater than the speed of light

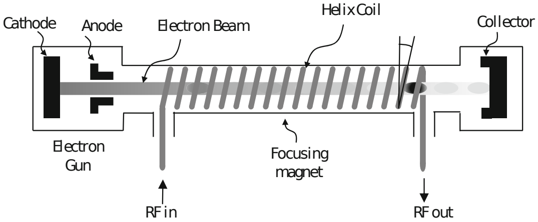
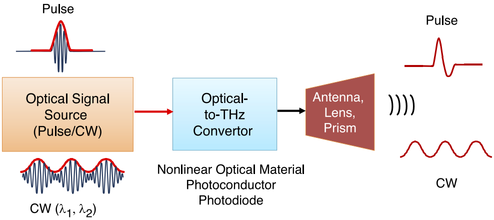


Figure 3: A typical vacuum-tube source [Rieh, J-S., Intro to Terahertz Electronics, Springer (2021)].



- The main idea is the optical-THz signal conversion through lasers
- Non-linear optical (NLO) materials are used to generate *monochromatic* THz waves
  - II-VI Semiconductor crystals such as ZnTe, and CdTe are commonly used as NLO materials

PLASMONICS

- Interfacial wave phenomena
  - Metal-dielectric interface
  - Semiconductor heterostructure
- Surface plasmon polaritons (SPPs)
- Plasma frequency
  - Metals — Optical frequency
  - Semiconductors — Terahertz

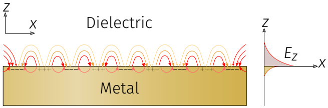


Figure 4: SPPs at optical frequencies

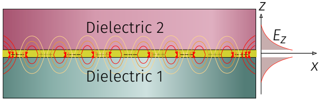


Figure 5: SPPs in the THz regime

- Slow surface waves
- Reduced Wavelength
- Focusing beyond the diffraction limit
- Optical SPP

$$\mathrm{Re}\left[\varepsilon_{\mathsf{metal}}(\omega)\right] < 0$$

- THz SPP

$$\mathrm{Im}\left[\sigma_{\mathsf{s}}(\omega)\right] < 0$$

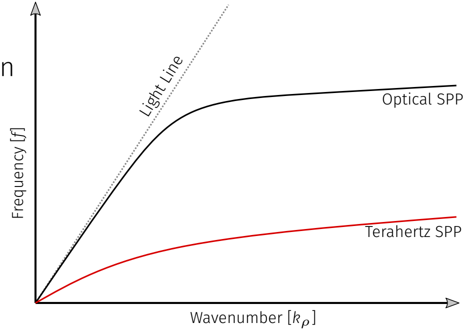


Figure 6: Dispersion Curve comparison

- Convert Localized near-field to efficient far-field radiation
- Low Q-factor
- Tiny size
- High Purcell Factor

$$P = \frac{Q}{V}$$

- Directive radiation

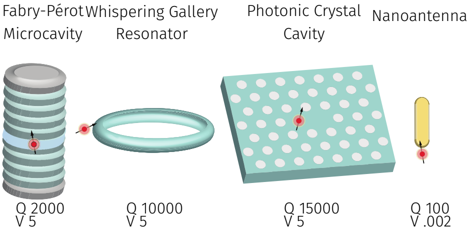
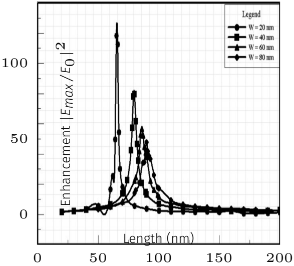
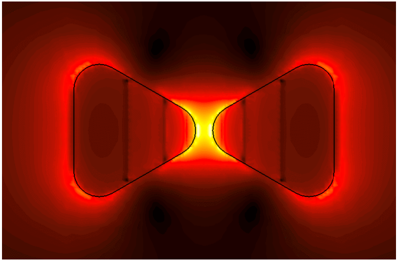
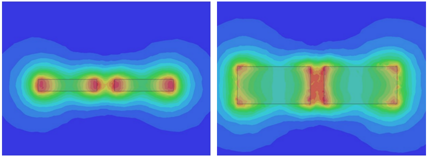


Figure 7: Optical resonant cavities for electric field enhancement

- Scaled-down microwave antenna designs
- Shift of resonance with width unlike in microwave regime







- Semiconductor Heterostructure in high electron mobility transistor (HEMT)
- High concentration of free electrons ($\sim 1 \times 10^{11} - 1 \times 10^{14}$ cm^{-2})
- Very high Mobility ($\sim 1 \times 10^{3} - 1 \times 10^{6}$ cm^{2}/V/s)
- Formation of Quantum Well
  - Two-dimensional confinement of electrons

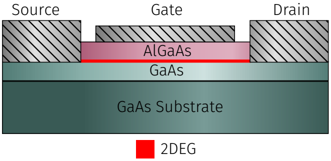


Figure 8: Typical GaAs/AlGaAs HEMT

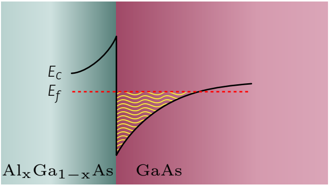
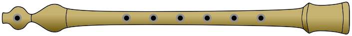
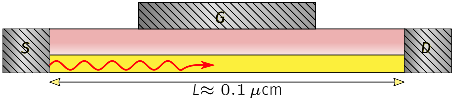


Figure 9: Band diagram of a GaAs/AlGaAs heterostructure

2DEG (contd.)

- Plasma waves in 2DEG
- Dyakonov-Shur instability
  - Voltage bias at source and drain terminals
  - Plasma resonance
  - THz emission
- Electronic Flute
  - Tunable resonance with gate voltage





$$\lambda = \frac{c}{f}$$

$$\implies 300\mu\text{m}$$

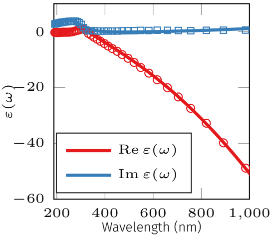
- SPP solution (pole expression)

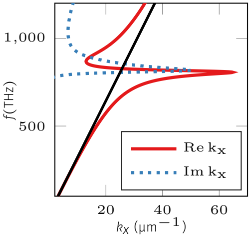
$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2(\omega)}{\varepsilon_1 + \varepsilon_2(\omega)}}$$

- Accurate material description

$$\varepsilon_2(\omega) = \varepsilon_\infty - \frac{\omega_d^2}{\omega^2 - j\gamma\omega} + \sum_{i=1}^{N} G_i(\omega)$$

$$G_i(\omega) = C_i \left[\frac{e^{j\phi_i}}{\omega_i + \omega - j\Gamma_i} + \frac{e^{-j\phi_i}}{\omega_i - \omega + j\Gamma_i} \right]$$





- Drude-Lorentz Surface Conductivity

$$\sigma_S = \frac{N_S e^2}{m^*} \frac{\tau}{1 + j\tau\omega}$$

N_S — Surface charge density

τ — Scattering time

m^* — Effective electron mass

- Equivalent Circuit

$$\sigma_S = \frac{1}{Z} = \frac{1}{R + 1/j\omega C}$$

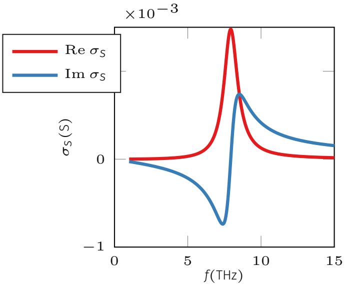
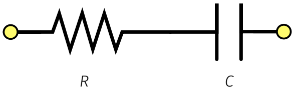


Figure 10: Room temperature GaN/AlGaN 2DEG surface conductivity

$Z = R - \frac{j}{\omega C}$



- Conductive Sheet in free space
- TM mode surface wave

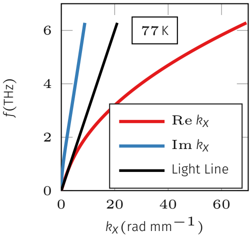
$$k_{\mathrm{P}}^{\mathrm{TM}} = \frac{\omega}{c}\sqrt{1 - \left(\frac{2}{\eta_0 \sigma_s}\right)^2}$$

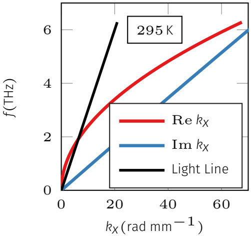
- Below plasma frequency

$$\mathrm{Im}\,\sigma_s < 0$$

- At low temperature

$$\mathrm{Im}\,|\sigma_s| \gg \mathrm{Re}\,|\sigma_s|$$





METASURFACES

- Mould the shape of a wavefront
- Challenge — Below optical frequencies, the EM wave loses its coherence when we move away from the source

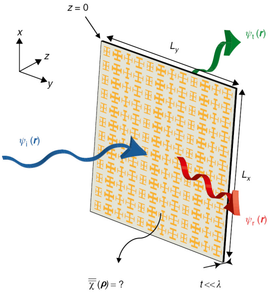


Figure 11: A metasurface illustration, from [Achouri, Karim and Caloz, Christophe. Nanophotonics, vol. 7, no. 6, 2018].

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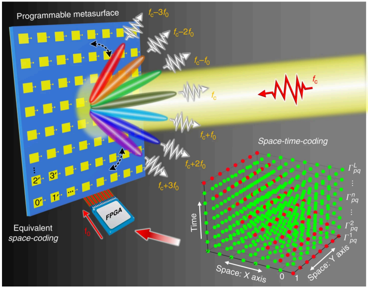


Figure 12: Programmable Metasurface, from [Zhang, L., Chen, X.Q., Liu, S. et al. Nat Commun 9, 4334 (2018)].

TERAHERTZ APPLICATIONS

Relying on the principle of reciprocity, we can use photoconductive antennas to detect THz radiation.

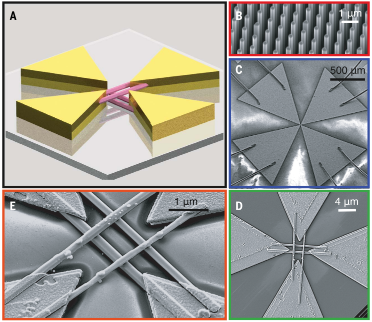
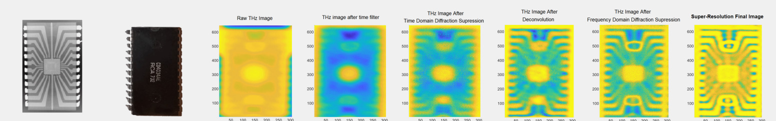


Figure 13: A polarisation sensitive cross-nanowire THz detector [Peng et al., Science 368, 510-513 (2020)].

- THz waves have the ability to see through apparently opaque objects.
- This is done in a non-ionising manner
- Through image processing, we can achieve high-resolution imaging through THz waves.

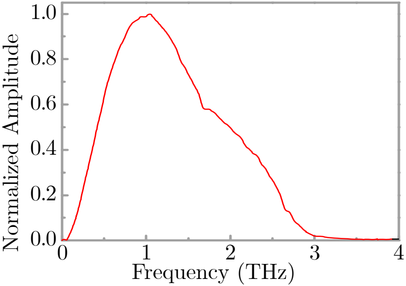


X-Ray Image

Optical Image
(a packaged IC)

High resolution Terahertz Image and steps of developing it

- THz time-domain spectroscopy (THz-TDS) is a well-known method for charaterising the material properties of different substances
  - Attractive applications in explosives detection, counterfeit drug discovery and health monitoring of plants
- The Biggest feature is again, the non-ionising nature of THz waves
- Common substances such as H_2O and N_2 have strong absorption spectra



2,4,6-Trinitrotoluene
(TNT)